

Claims

- [c1] A method for reducing a spurious signal in a nuclear magnetic resonance (NMR) measurement, comprising:
 inducing a static magnetic field in a volume to polarize spins of nuclei therein;
 inducing an RF magnetic field in the volume in accordance with a pulse sequence;
 acquiring a sequence of signals generated in the volume in response to the pulse sequence, each signal in the acquired sequence including a spurious signal component and a spin echo component;
 combining at least a first signal and a second signal of the acquired sequence, thereby generating a corrected signal having a reduced spurious signal component.
- [c2] The method as recited in claim 1, wherein the corrected signal is generated from a linear combination of at least the first signal and the second signal.
- [c3] The method as recited in claim 2, wherein the linear combination is the average of at least the first signal and the second signal.
- [c4] The method as recited in claim 1, wherein the second signal is adjacent the first signal in the acquired sequence.
- [c5] The method as recited in claim 1, wherein the second signal is a next nearest neighbor of the first signal in the acquired sequence.
- [c6] The method as recited in claim 1, wherein a time delay between the first signal and the second signal in the acquired sequence is less than 10 milliseconds.
- [c7] The method as recited in claim 1, wherein a time delay between the first signal and the second signal in the acquired sequence is in the range of 0.5 to 5 milliseconds.
- [c8] The method as recited in claim 1, comprising computing an NMR parameter of the volume using the corrected signal.
- [c9] The method as recited in claim 8, wherein the NMR parameter is a T_2

distribution.

- [c10] The method as recited in claim 8, comprising deriving a geological characteristic of the volume based on the computed NMR property.
- [c11] The method as recited in claim 10, wherein the geological characteristic is porosity.
- [c12] The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses, and wherein at least one of the inversion pulses is phase alternated relative to the others.
- [c13] The method as recited in claim 1, wherein the pulses of the pulse sequence are arranged to compensate for spin dynamics errors.
- [c14] The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is six inversion pulses arranged to induce a phase pattern of six spin echo signals in accordance with the following:

$$+X_1(-\gamma_1)-X_2(+\gamma_2)-X_3(-\gamma_3)+X_4(+\gamma_4)+X_5(-\gamma_5)+X_6(+\gamma_6)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c15] The method as recited in claim 14, wherein the linear combination is selected from the group consisting of:

$$(a) \quad lc_1 = \frac{1}{2}(e_1 + e_j) \quad i = 1, 4, 7, \dots, j = 3, 6, 9, \dots;$$

$$(b) \quad lc_2 = \frac{1}{2}(e_1 + e_j) \quad i = 2, 5, 8, \dots, j = 3, 6, 9, \dots;$$

$$(c) \quad lc_3 = \frac{1}{2}(e_1 + e_j) \quad i = 3, 6, 9, \dots, j = 4, 7, 10, \dots;$$

$$(d) \quad lc_4 = \frac{1}{2}(e_1 + e_j) \quad i = 3, 6, 9, \dots, j = 5, 8, 11, \dots;$$

wherein lc represents the linear combination, and e represents the induced spin echo signal.

- [c16] The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a

phase pattern of three spin echo signals in accordance with the following:

$$+Y_1(+\gamma\delta)-Y_2(+\gamma\delta)-Y_3(+\gamma\delta)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c17] The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a phase pattern of three spin echo signals in accordance with the following:

$$+Y_1(+\gamma\delta)+Y_2(+\gamma\delta)-Y_3(+\gamma\delta)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c18] The method as recited in claim 1, comprising computing a first reconstructed signal and a second reconstructed signal from the corrected signal, the first and second reconstructed signals representative of the respective spin echo components of the first and second signals of the acquired sequence.

- [c19] A method of reducing a ringing signal generated while measuring a nuclear magnetic resonance (NMR) property of an earth formation adjacent a borehole, comprising:
 inserting a logging tool into the borehole;
 applying a static magnetic field to polarize spins of nuclei within a volume of the earth formation;
 applying an RF magnetic field to the volume in accordance with a pulse sequence comprising a plurality of inversion pulses arranged in a repeating phase pattern;
 acquiring, after each of the plurality of pulses in the pulse sequence, a spin echo signal induced in the volume, thereby forming a measurement set comprising a plurality of spin echo signals, each spin echo signal including a spin echo component and a ringing component; and
 combining spin echo signals within the measurement set to reduce the ringing

components, thereby generating a corrected measurement set.

- [c20] The method as recited in claim 19, wherein the combining comprises forming a linear combination of spin echo signals within the measurement set.
- [c21] The method as recited in claim 19, comprising determining, from the corrected measurement set, an NMR parameter of the earth formation.
- [c22] The method as recited in claim 21, comprising deriving from the NMR parameter a property of the earth formation.
- [c23] The method as recited in claim 19, wherein the acquiring is performed while drilling the borehole.
- [c24] The method as recited in claim 19, wherein at least one of the inversion pulses in the repeating phase pattern is phase alternated relative to the others.
- [c25] The method as recited in claim 19, wherein the inversion pulses in the repeating phase pattern are arranged to compensate for spin dynamics errors.
- [c26] The method as recited in claim 19, wherein the repeating phase pattern of inversion pulses is six inversion pulses arranged to induce a pattern of six spin echo signals in accordance with the following:

$$+X_1(-\gamma_1)-X_2(+\gamma_2)-X_3(-\gamma_3)-X_4(+\gamma_4)+X_5(-\gamma_5)+X_6(+\gamma_6)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c27] The method as recited in claim 26, wherein the combining comprises forming a linear combination of spin echo signals within the measurement set, and the linear combination is selected from the group consisting of:

$$(a) \quad lc_1 = \frac{1}{2}(e_1 + e_j) \quad i = 1, 4, 7, \dots, j = 3, 6, 9, \dots;$$

$$(b) \quad lc_2 = \frac{1}{2}(e_1 + e_j) \quad i = 2, 5, 8, \dots, j = 3, 6, 9, \dots;$$

$$(c) \quad lc_3 = \frac{1}{2}(e_i + e_j) \quad i = 3, 6, 9, \dots, j = 4, 7, 10, \dots;$$

$$(d) \quad lc_4 = \frac{1}{2}(e_i + e_j) \quad i = 3, 6, 9, \dots, j = 5, 8, 11, \dots;$$

wherein lc represents the linear combination, and e represents the induced spin echo signal.

- [c28] The method as recited in claim 19, wherein the repeating phase pattern of inversion pulses is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+Y_1(+\gamma) - Y_2(+\gamma) - Y_3(+\gamma)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and wherein the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c29] The method as recited in claim 19, wherein the repeating phase pattern of inversion pulses is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+Y_1(+\gamma) + Y_2(+\gamma) - Y_3(+\gamma)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c30] The method as recited in claim 19, comprising computing a set of first reconstructed signals from the corrected measurement set, the set of reconstructed signals representative of the respective spin echo components of the acquired spin echo signals.

- [c31] A method for determining an earth formation property from nuclear magnetic resonance (NMR) measurements, comprising:
 acquiring a first measurement set of spin echo signals induced in the earth formation by a first RF pulse sequence, the spin echo signals including a spin echo component and a noise component;
 linearly combining spin echo signals within the first measurement set to reduce the noise component, thereby generating a first corrected measurement set;
 determining an NMR parameter based on the first corrected measurement set;
 and
 deriving the earth formation property from the NMR parameter.

- [c32] The method as recited in claim 31, wherein the linearly combining is restricted to only combinations of spin echo signals that reduce the noise component.

- [c33] The method as recited in claim 31, wherein the NMR parameter is a T_2 distribution.
- [c34] The method as recited in claim 31, wherein the acquiring is performed while drilling a borehole traversing the earth formation.
- [c35] The method as recited in claim 31, comprising:
 acquiring a second measurement set of spin echo signals induced in the earth formation by a second RF pulse sequence, the second RF pulse sequence being phase alternated relative to the first RF pulse sequence, the spin echo signals of the second measurement set including a spin echo component and a noise component;
 linearly combining spin echo signals within the second measurement set to reduce the noise component, thereby generating a second corrected measurement set;
 combining the first corrected measurement set with the second corrected measurement set; and
 determining the NMR parameter based on the first and second corrected measurement sets.
- [c36] The method as recited in claim 31, wherein the first RF pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is six inversion pulses arranged to induce a pattern of six spin echo signals in accordance with the following:

$$+X_1(-\gamma_1)-X_1(+\gamma_2)-X_1(-\gamma_3)-X_1(+\gamma_4)+X_5(-\gamma_5)+X_6(+\gamma_6)$$
 wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.
- [c37] The method as recited in claim 36, wherein linearly combining comprises forming at least one linear combination from the group consisting of:
- (a) $lc_1 = \frac{1}{2}(e_i + e_j)$ $i = 1, 4, 7, \dots, j = 3, 6, 9, \dots$;
 - (b) $lc_2 = \frac{1}{2}(e_i + e_j)$ $i = 2, 5, 8, \dots, j = 3, 6, 9, \dots$;
 - (c) $lc_3 = \frac{1}{2}(e_i + e_j)$ $i = 3, 6, 9, \dots, j = 4, 7, 10, \dots$;
 - (d) $lc_4 = \frac{1}{2}(e_i + e_j)$ $i = 3, 6, 9, \dots, j = 5, 8, 11, \dots$;

wherein c represents the linear combination, and e represents the induced spin echo signal.

- [c38] The method as recited in claim 31, wherein the first RF pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+Y_1(\gamma_1)-Y_2(\gamma_2)-Y_3(\gamma_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c39] The method as recited in claim 31, wherein the first RF pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+Y_1(\gamma_1)+Y_2(\gamma_2)-Y_3(\gamma_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

- [c40] The method as recited in claim 31, comprising computing a first reconstructed signal and a second reconstructed signal from the corrected signal, the first and second reconstructed signals representative of the respective spin echo components of the first and second signals of the acquired sequence.